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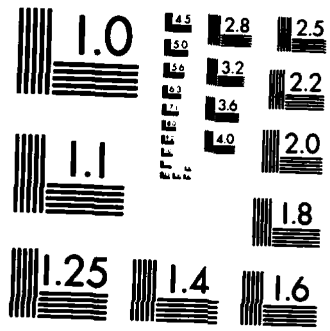

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ELECTROMAGNETIC INSPECTION OF WIRE ROPES USING SENSOR ARRAYS

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Quarterly Progress Report for Period
16 September 1984 - 15 December 1984

Prepared for

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QUARTERLY PROGRESS REPORT

16 September 1984 - 15 December 1984

Summary

In the time period between 16 September 1984 and 15 December 1984, we achieved the following:

- ~~We~~ implemented and evaluated a procedure and prototype instrumentation for the inspection of wire rope end sections. Laboratory experiments clearly demonstrate the viability of this approach; however, a considerable amount of field testing and further development will be required to make this procedure sufficiently rugged and reliable under adverse field conditions.

- We modified our cassette tape recorder data acquisition circuitry to make it useful for end section inspections.

- We modified our mechanical rope position transducer to drastically increase its resolution in order to make it useful for end section inspections.

- We developed circuitry for the automatic calibration of the LMA channel.

- Two instruments were sold to British Aerospace. These instruments are intended to be used by the British Navy to inspect tow cables for submarine detection equipment.

1. Instrument for the Inspection of Wire Rope End Sections.

During operation, moving and standing wire ropes are subjected to, sometimes severe, vibrations which excite longitudinal, lateral and torsional rope oscillations. For all types of rope oscillations, longitudinal, lateral or torsional, rope terminations constitute oscillation nodes, causing a major part of the oscillatory energy in the rope to be absorbed by the end attachment.

Hence, rope oscillations induce considerable tension, bending and torsional stresses at the rope terminations which cause the wires to fatigue and, eventually, to break. Rope breakage at the end attachments is a common failure mode. This makes rope terminations a very critical area in assessing a rope's condition.

A typical form of vibrational fatigue occurs in installations subject to cyclic loading, for instance in the boom suspension systems of draglines. Here, the vibrational energy, induced by cyclical loading of the rope, is absorbed at the end fittings of the pendants causing eventual fatigue breakage at this point.

Another example: Normal operation of a machine or hoist induces oscillations. For instance, in shaft hoists, start up of the cage at the bottom excites low frequency oscillations in the rope. As the cage reaches the top of the shaft, the free length of rope becomes

much shorter and the initial slow oscillation turns into a high-frequency vibration. A major part of the vibrational energy is dissipated in the cage attachment, resulting in eventual fatigue breakage of the wires at the attachment of the cage.

As discussed previously, none of the present NDI instruments is, even remotely, useful for the inspection of wire rope end sections. One of the objectives of the present R&D is to remedy this situation, and to develop instrumentation and a procedure for end section inspection.

During the current reporting period, we implemented a first prototype instrument for the inspection of wire rope end sections. We designed, manufactured and evaluated an "end section coil" which can be attached to a regular instrument as shown in Figure 1.

As expected, first experiments indicated that the greatly distorted magnetic field close to the rope termination socket can conceal the relatively small distortions of the magnetic field caused by defects. The minute defect signals, superimposed on the signals caused by the grossly distorted field, are hard to identify and evaluate.

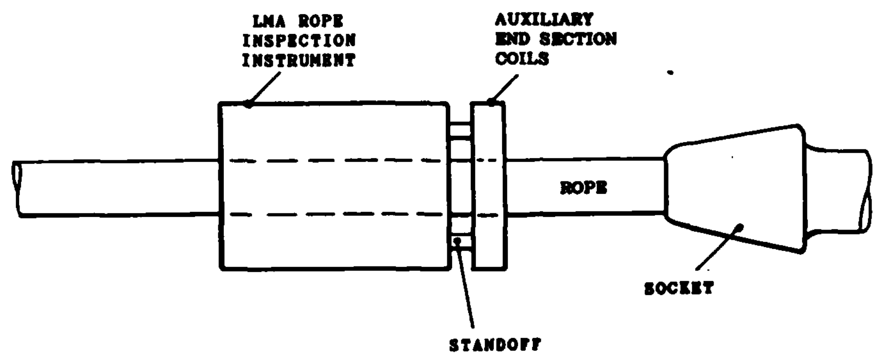

Figure 1: Instrumentation for the Inspection of Wire Rope End Sections

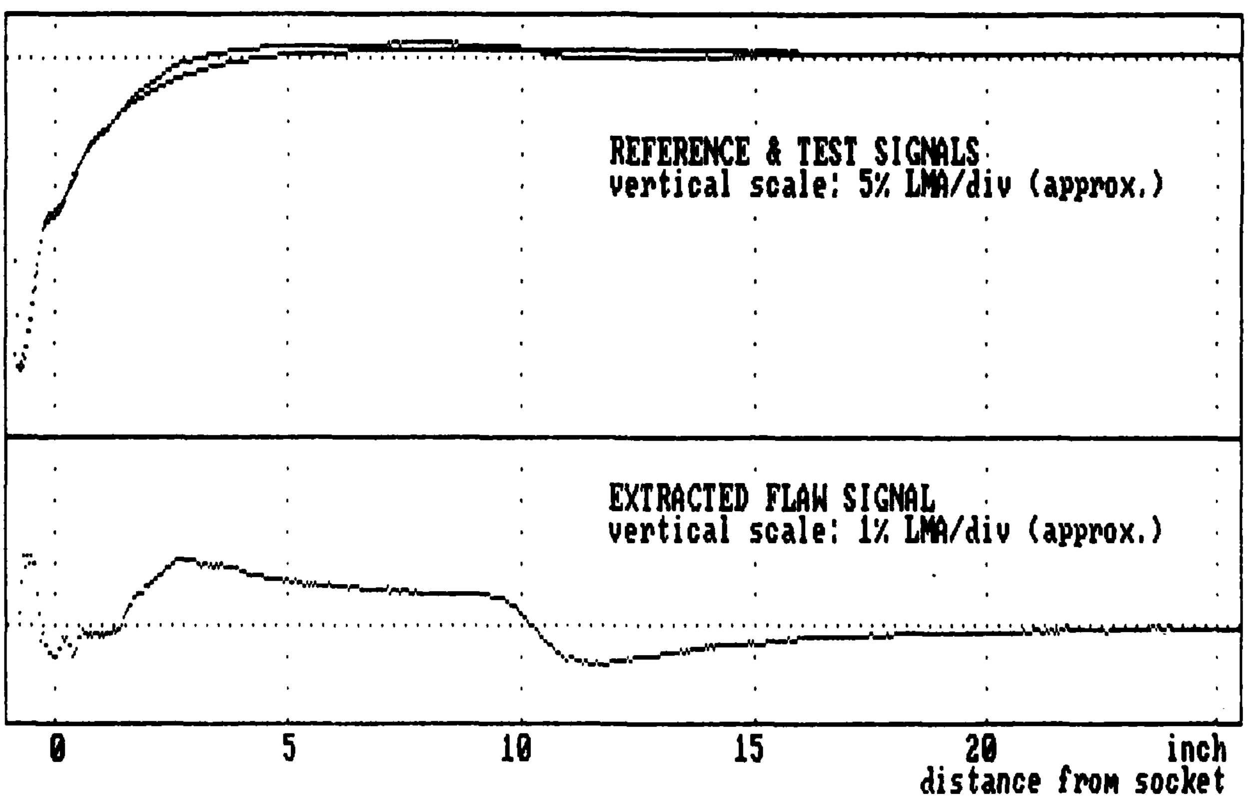

Figure 2: End Section Inspection: Test Results

Because of this problem, the determination of defects ultimately has to be based on a comparison of subsequent inspection results, and a basic inspection program of the following type should be implemented:

1. To establish baseline data for subsequent inspections, the program has to be initiated by a first inspection of the new rope after its installation and after a sufficient break-in period. This baseline inspection yields the "Reference Signal."

2. Successive periodic inspections are performed at predetermined intervals. These inspections yield the "Test Signals."

3. All inspection results are compared with the results of the baseline inspection. Defects will be indicated by deviations of the Test Signal from the Reference Signal.

Since the magnetic field in the rope is drastically distorted by the rope termination, defects are indicated by relatively minuscule deviations of the Test Signal from the Reference Signal. Therefore, to allow a reliable and accurate comparison of successive test results, the following two conditions have to be satisfied by the test instrumentation:

1. Test results must be reproducible with extraordinary accuracy and reliability, and

2. the comparison of test results has to be performed with great accuracy and resolution.

In particular, to make test results reproducible, the following conditions must be satisfied:

- o Test results must be completely independent of the azimuthal position of the instrument with respect to the rope.

  Because the magnetizer assembly as well as the attached end section coils have almost perfect rotational symmetry, this condition is satisfied for our bigger prototype instruments.

  Note that that rotational symmetry is hard to achieve for instruments which use discrete sensors, such as Hall Generators or Flux Gate Sensors, for magnetic field sensing.

- o Test signals amplitudes must be independent of rope speed.

  Because our sensor design uses sense coils together with signal integration, this condition is automatically satisfied for both, the LMA and the LF signal.

- o The position of the test signal with respect to the rope longitudinal axis must be determined with great accuracy and

resolution.

Our incremental optical encoder was modified to allow position sensing with a resolution of approximately 0.042". This resolution is sufficient to achieve excellent repeatability of the test results.

- The magnetic state of the rope, prior to the test, must be accurately reproducible to avoid a distortion of the defect signal due to the remagnetization effect.

  Problems caused by remagnetization of the rope can be avoided by magnetically homogenizing the rope before the inspection. Homogenization is achieved by simply moving the rope through the instrument once before the inspection.

  The socket, which is made from steel, could also become permanently magnetized in a random fashion. Although, in our lab experiments, we have not encountered any random magnetization of the socket, problems of this type are conceivable. Eventually, some procedure might have to be designed to bring the socket into a well defined magnetic state prior to the inspection.

To allow an accurate comparison of test result obtained from different inspections, our data acquisition system, comprising an IBM PC XT computer including analog/digital interface circuitry, is

well suited. The following procedure was used for our lab experiments:

1. The instrument, with the end section coil and position transducer (incremental encoder) attached, is mounted on the rope at a distance of approximately 15' from the socket, with the end section coil facing toward the rope socket.

2. To magnetically homogenize the rope, the instrument is moved toward the socket as far as possible until the magnetizer assembly touches the socket. Note that the inner coil diameter is larger than the diameter of the socket, and the end section coil can be moved approximately 1/2" beyond the end of the socket. The rope is now homogenized and in a well defined magnetic state.

3. The data acquisition system is set up and programmed in such a fashion that the sampling of data points is clocked by pulses from the incremental encoder at a sampling rate of approximately 24 samples/inch. This approach, together with the previously discussed procedures, makes data acquisition independent of time and completely reproducible.

4. The computer data acquisition program is now started.

5. The instrument is manually moved away from the rope socket. As the instrument moves, the incremental encoder produces pulses at

a rate of approximately 24 pulses/inch. Each pulse triggers sampling of one data point. The sampled test data points are stored on hard disk.

6. To initiate the lab experiments, an inspection of the sample rope, including socket, in its original condition is performed. These inspection results are stored on disk and serve as the reference signal.

7. Defects are simulated by attaching short pieces of wire to the rope. The above test procedure is repeated for the rope with simulated rope flaws. The test signal is stored in the computer on disk.

8. A separate computer program compares the Reference Signal with the Test Signal. Since both signals are reproducible with considerable accuracy and resolution, this can be accomplished by simply subtracting corresponding stored data points of the two signals.

Figure 2 shows test results obtained from an end section inspection using an LMA-175 instrument including an end section coil and an incremental optical encoder. The experiment was performed according to the above procedure.

The reference signal was acquired and stored on disk by inspecting the rope close to the end section in its original condition. An 8 inch long wire with a metallic cross-sectional area of approximately 1.4% of the total rope cross-sectional area was attached to the rope with one wire end at a distance of 2 inches from the socket. With this wire attached, the rope was then inspected and the test signal was also stored on disk.

The upper part of Figure 2 shows the Reference Signal and the Test Signal. Note the drastic distortion of both signals, caused by the socket and the rope end.

Using the computer, the flaw signal was then extracted from both signals by subtracting the Reference Signal from the Test Signal. The extracted flaw signal is shown in the lower part of Figure 2.

Note that, close to the rope terminations, even small deviations of the relative position of the two signals can cause drastic inaccuracies in the extracted flaw signal. Therefore, the computer program allows for a micro-adjustment of the absolute position of both signals by plus or minus one sample point (equivalent to a distance of +-0.042 inches). The adjustment is accomplished by interpolation. At this stage of the research, the micro-adjustment is performed visually, on the computer monitor screen, by trial and error. Conceivably, in the future, the position micro-adjustment could be performed automatically by a simple computer algorithm.

In Figure 2, the LMA signal is distorted as compared to the shape of the LMA signal caused by the same flaw in an instrument with our regular symmetrical sensor-magnetizer arrangement. A computer simulation shows this deformation to be caused by the unsymmetrical coil-magnetizer geometry. Since the phenomenon is well understood, a computer algorithm can probably be designed to eliminate this distortion.

2. Data Acquisition System

Since end section inspections will have to be performed in the field, and since ruggedized and portable computer hardware for the on-site evaluation of test results is not immediately available, the evaluation of test results will have to be performed off-line in the lab. Test results have to be stored on some medium which allows data storage and transfer to the computer.

For regular inspections, we had previously developed FM and FSK interface circuitry which allows the use of any stereo cassette tape recorder as a data acquisition recorder. This circuitry allows simultaneous recording of the LMA and LF signals together with the rope footage counter signals.

However, our previous data acquisition system is no longer adequate for end section inspections. Besides the LMA and LF

signals, the high-frequency position signal, which controls the sampling of data points by the computer, has to be stored on the tape. Since a stereo tape deck has only two tracks, the LF channel and the position signal channel have to be accommodated on the same track. For regular instruments, which require a position pulse only every 10 feet or so, this poses no problem. Here, the position signal requires an FSK frequency range of much less than 1 kHz.

For end section inspection, however, an A/D sampling frequency of 24 pulses/inch is required. At inspection speeds of 500 ft/min, this requires an FSK frequency band of at least 6 kHz, with the frequency range of the tape recorder restricted to only 16 kHz.

We started a development effort to accommodate a high-frequency FSK channel together with the LF signal channel on one tape track. However, after approximately 2 weeks into this development, it became obvious that a very major effort would be required to accomplish our goal.

Therefore, we decided to store the position signal (A/D trigger pulses) on one tape track, and the LMA or LF signal on the other track. The LMA and LF signals, including their respective timing pulses, can then be recorded separately in two subsequent inspection runs. Since the test results are very accurately reproducible, it is then easy to display and correlate both signals simultaneously by using the computer.

The interface circuitry is now completely developed, and it is sufficient and reliable for end section inspections. For regular inspections, our previous interface circuitry, which allows a simultaneous recording of the LMA, LF and (low frequency) position signals, can be used.

At a later date, we plan to acquire a 4-track 4-channel cassette tape recorder. Using our data acquisition circuitry, this recorder will allow simultaneous recording of up to four different signals simultaneously.

Eventually, ruggedized portable computers, suitable for data acquisition and processing applications, will become available. They can then be used, on-site, for in-service end-section inspections. They would have the advantage that test results can be immediately evaluated. Any doubts or discrepancies concerning the test results can then be directly investigated and resolved on-site.

We are presently considering a portable COMPAQ-Plus Personal Computer for our data acquisition applications. This portable computer is completely equivalent to the IBM PC XT and compatible with our present data acquisition system. The COMPAQ computer has only two minor drawbacks: It is not battery operated and requires an electrical outlet which might cause some inconvenience under certain field conditions, and, although portable and rugged, it appears

primarily intended for office use.

3. Instrument Calibration.

We implemented the new automatic calibration procedure, including circuit hardware, which we mentioned in our previous progress report. The calibration procedure allows a reading of a rope's loss of metallic cross-sectional area as a percentage of the rope's total metallic cross-sectional area.

The calibration procedure is very simple. It consists of the following steps:

1. Connect the instrumentation with all necessary connector cables and turn on power.

2. With the Sense Head closed, push the Reset Button.

3. Mount instrument on the rope.

4. To homogenize the rope, move approximately 6 feet of the rope through the instrument in the forward direction and then approximately 3 feet in the reverse direction.

5. Push the Calibrate Button. The instrument is now calibrated with a calibration factor of .05 V/%LMA.

5. Push Reset Button again.

6. Run test.

The calibration procedure is based on the fact that mounting of the instrument on the rope amounts to a 100% increase of metallic cross-sectional area as measured by the instrument. Pushing the Calibration Button automatically adjusts the gain of the calibration amplifier in such a fashion that, with any input signal, its output becomes 5 V. This calibrated gain setting is digitally stored and retained indefinitely as long as the power remains turned on.

The calibration circuit works reliably. However, for closely spaced ropes such as elevator ropes, the calibration setting is significantly influenced and distorted by the adjacent ropes. Magnetic interference, which can never be completely avoided, causes this problem. The previously described manual calibration procedure, using reference wires which are attached to the rope, should be used in these cases.

Manually setting the gain of the calibration amplifier is the preferred method for ropes with known parameters. For instance, if a regularly scheduled inspection program is instituted, the proper setting of the calibration potentiometer can be determined, once and for all, at the beginning of the test program.

4. Field Testing.

Field testing of our newly developed instruments has been difficult for us in the past. It is absolutely necessary because of the following reasons:

o Most of our experiments are performed in the lab under well controlled conditions. While these lab tests are indispensable for instrument development, they are often not a true reflection of instrument performance under actual and usually adverse field conditions.

We and some of our customers have encountered, in the past, some unexpected problems when our instruments were first exposed to field conditions. Our more experienced and sophisticated customers have reported these problems back to us, and we were usually able to correct them. The Mine Safety and Health Administration and the British National Coal Board were particularly helpful in this respect.

An example: The Mine Safety and Health Administration has reported problems inspecting tightly spaced elevator ropes with their recently acquired LMA-75 instrument. While the LF trace was completely normal, the LMA trace showed some unexplainable erratic behavior. As it turned out, the problem was caused by lateral random oscillations, with respect to the instrument, of adjacent ropes.

This lateral movement caused, via magnetic interference, a severe distortion of the LMA trace. The problem can be solved simply by restraining the ropes from moving laterally.

Field testing is particularly important for our bigger instruments. Our small lab test rig is restricted to ropes up to 3/4" diameter. Therefore, it is impossible to test our bigger instruments at their full capacity. This has caused considerable and expensive problems in the past.

For instance, when the LMA-175 instrument was first delivered to the British National Coal Board, the integrating operational amplifier, which worked perfectly well while inspecting our 3/4" test rope in the lab, saturated during the inspection of their 1 1/2" test rope. It took two trips to England to identify this relatively minor problem and to correct it.

In the past, the British National Coal Board has given us some valuable advice on how to ruggedize our instruments. The planned development of an intrinsically safe instrument, in cooperation with the Coal Board, is presently stalled by lack of funding.

To date, we have sold only some of our small and medium sized instruments, and none of our bigger rope testers. Especially our large LMA-250 instrument, for ropes up to 2 1/2" diameter, has never been tested in the field or at its full capacity. The purchase of an

LMA-250 instrument by the Mine Safety and Health Administration, which was planned, would have been of considerable help in evaluating this large instrument. Unfortunately, because of budgetary cutbacks, this acquisition did not materialize.

o For most of our potential customers, nondestructive wire rope inspection is a brand new development. Therefore, they are very skeptical and insecure as far as this type of instrumentation is concerned. Field evaluation of our instruments by an independent party would greatly alleviate this skepticism. It would add a measure of credibility, which will be necessary for successful marketing of our instruments and, potentially, inspection services.

The design of our LMA instruments could build on the, extensively published, field experience with nondestructive rope inspection which was accumulated over a time period of several decades. If nothing else, this experience demonstrated that nondestructive wire rope inspection is feasible.

Our End Section Inspection System, however, is a completely new development, and no previous field experience with this type of inspection is available, anywhere. End Section Inspection, now in its infancy, will require extensive field testing, possibly combined with some additional development, to make it a viable and accepted inspection procedure. For instance, end section inspections rely on an extremely accurate repeatability of test results. Therefore, the

question of repeatability of test results under field conditions is crucial and must be resolved.

Another important problem, which should be resolved by field testing, is the question of how test results are related to remaining rope strength and rope life. Although some results are available, they have to be viewed with considerable skepticism. Further research in this area is badly needed. To attack this problem, field tests should be combined with destructive laboratory tests and rope examinations. Because of the improvements which we have achieved in quantitative defect identification, we feel that we could make a contribution in this area.

5. Miscellaneous

Two LMA-125 instruments (for ropes up to 1 1/4" diameter) were sold to British Aerospace. These instruments are intended to be used by the British Navy for inspecting tow cables for submarine detection equipment. They will be delivered in May. In connection with this purchase, personnel from the British Ministry of Defence and British Aerospace will visit us in February 1985.

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